

Short Term Solar Forecasting Using Sky Imagery and Its Applications in Control and Optimization for a Smart Grid

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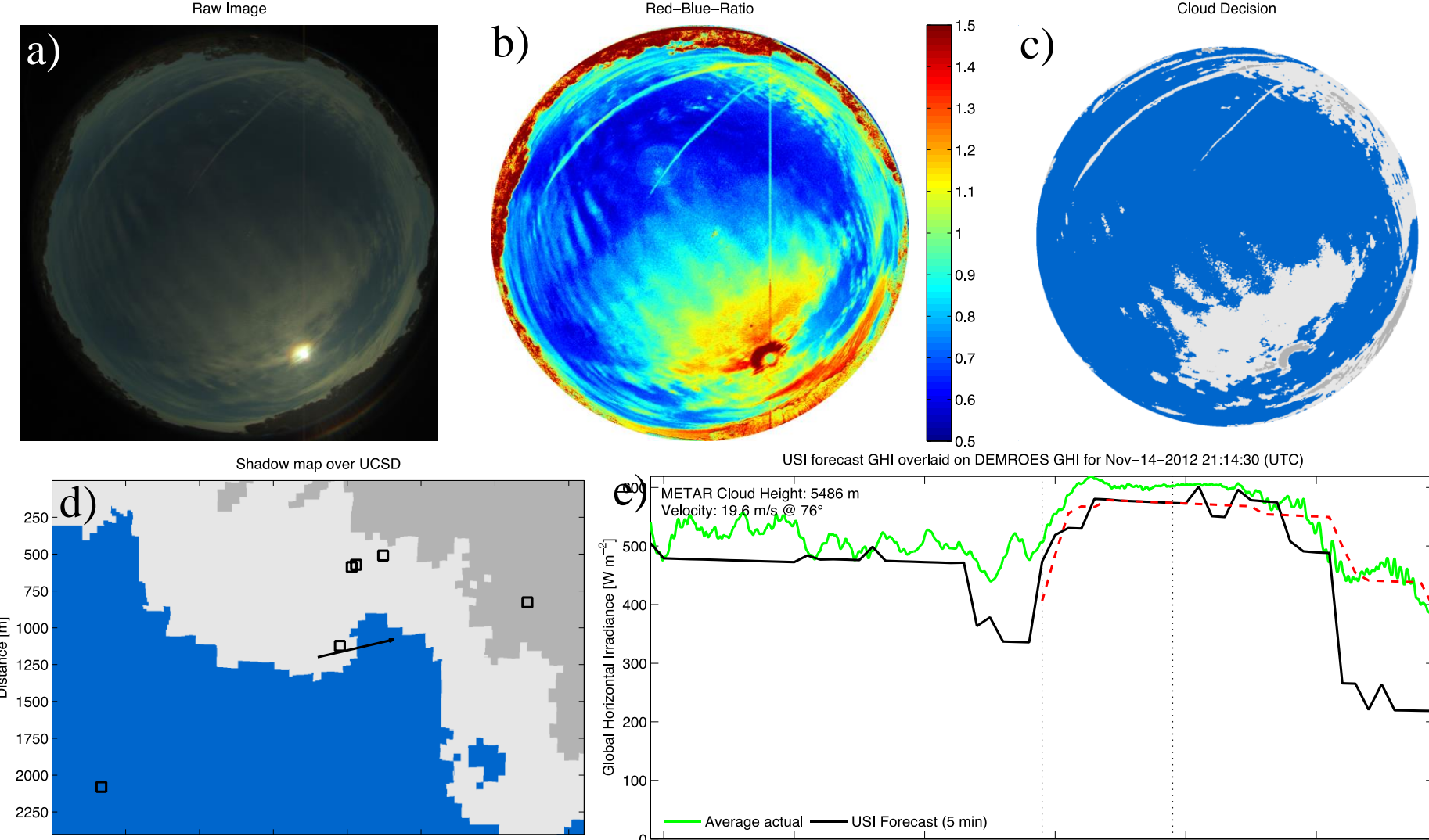
Short-term Solar Forecasting

Goal: Forecast solar generation in short time scale (0-30 minutes) with high temporal resolution to build smart controls for storage systems (charge/ discharge), power inverters, voltage regulators, smart switching devices, etc. This helps to save generation and maintenance cost while keeping power quality high.

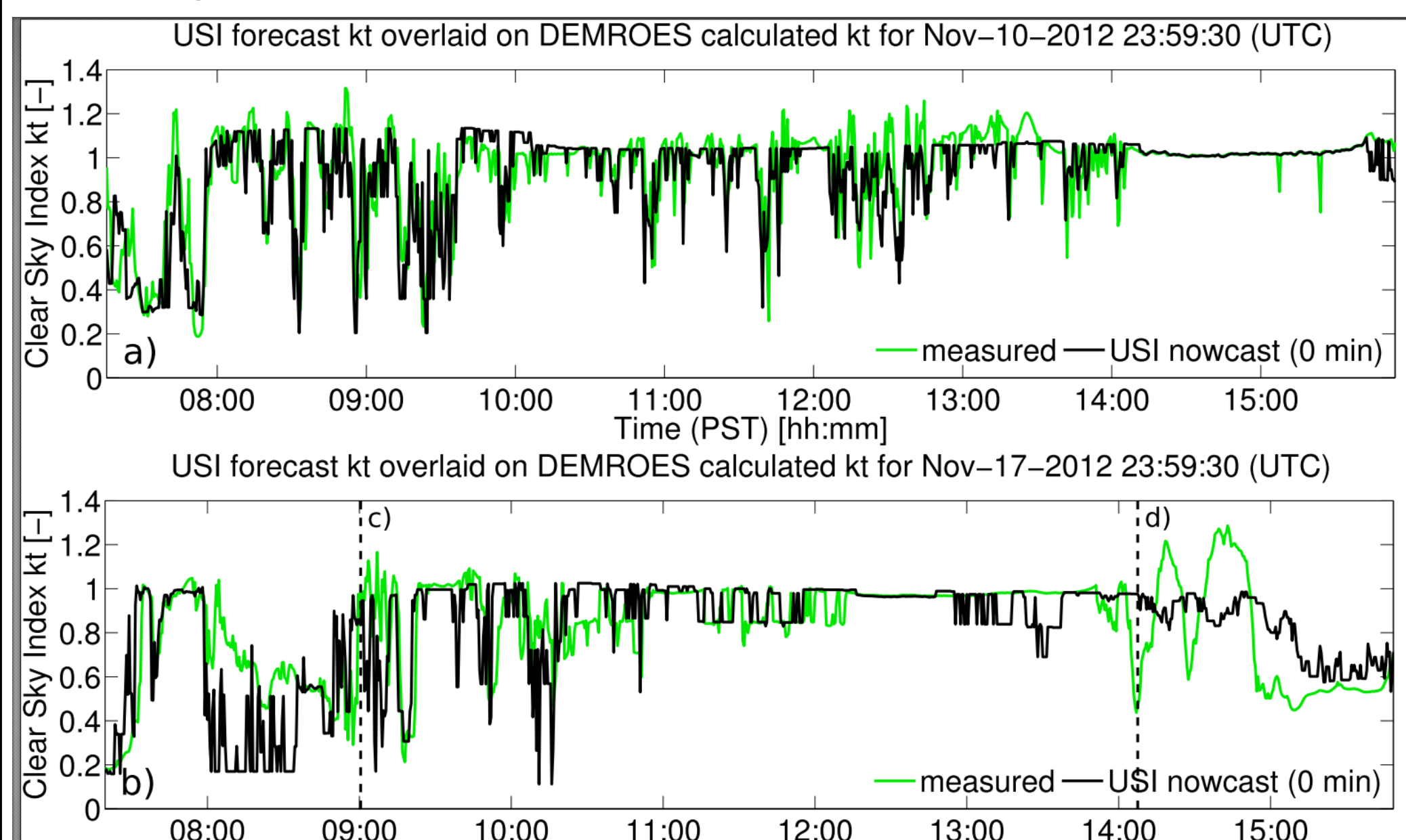


Algorithm: The fundamental idea is to detect cloud and predict its location in the future to determine whether and when it will cover the PV panels. The forecasting process includes several steps:

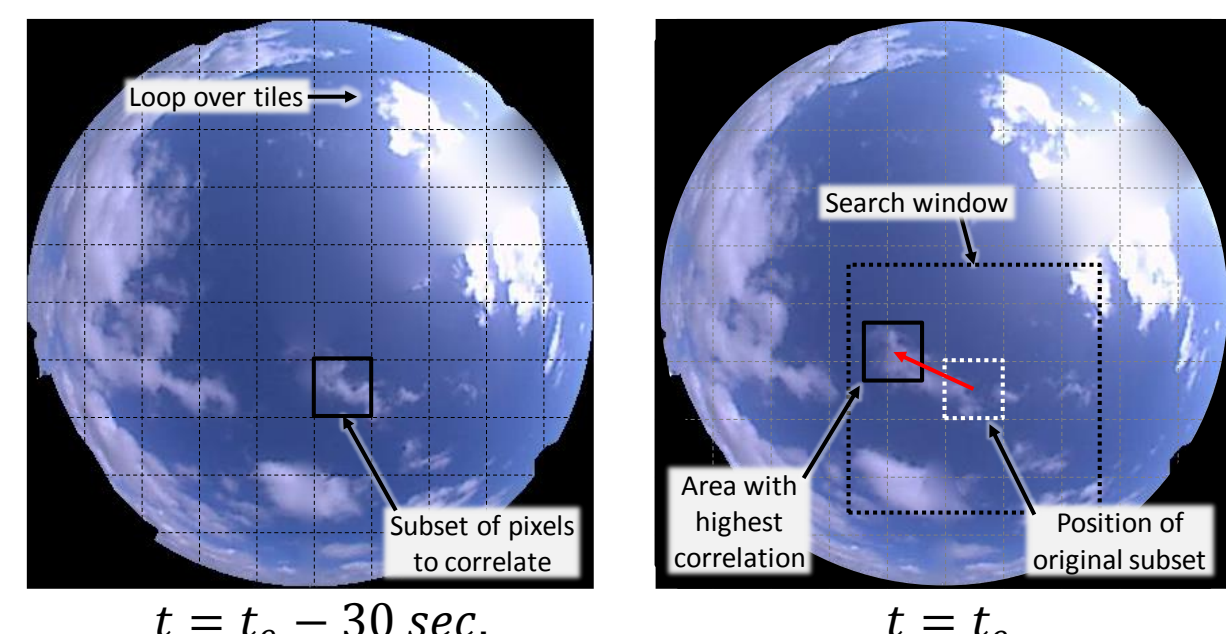
1. Cloud Detection: Using image processing to distinguish cloud from clear sky by RBR value.
2. Cloud projection into an earth coordinate system.
3. Cloud speed and direction calculation: Using image segment correlation.
4. Modeling cloud motion forward in time using the cloud detection and the motion vectors.
5. Projection of cloud shadows on the ground for irradiance forecasting of solar panels.



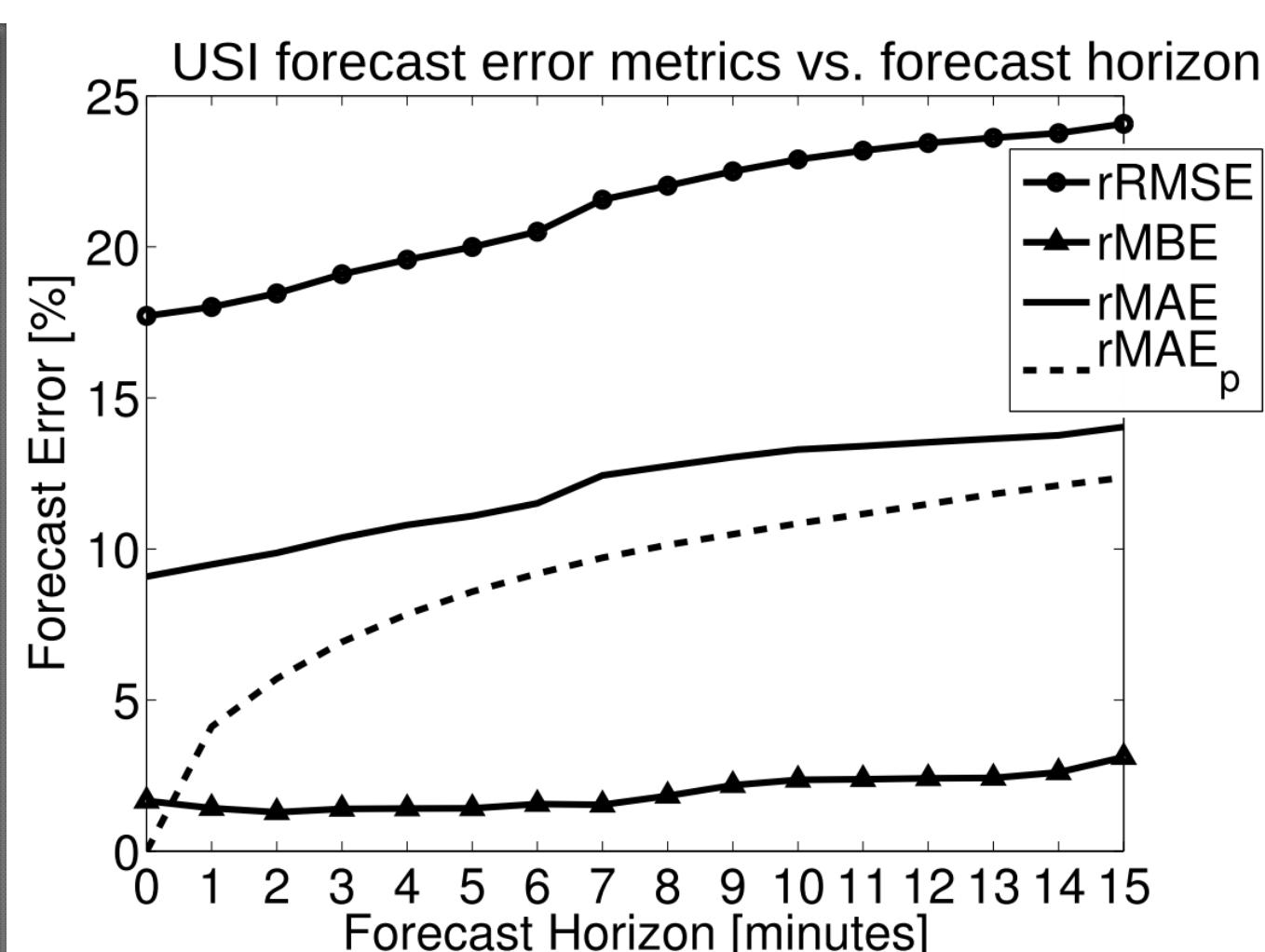
Sample of a forecast process done at UCSD. Green line is 5-minute forecast and black line is measured data.



USI forecast and measured *kt* averaged across 6 pyranometers at UCSD for Nov 10 and Nov 17 with cumulus clouds.



Cloud speed and direction calculation using image segment correlation

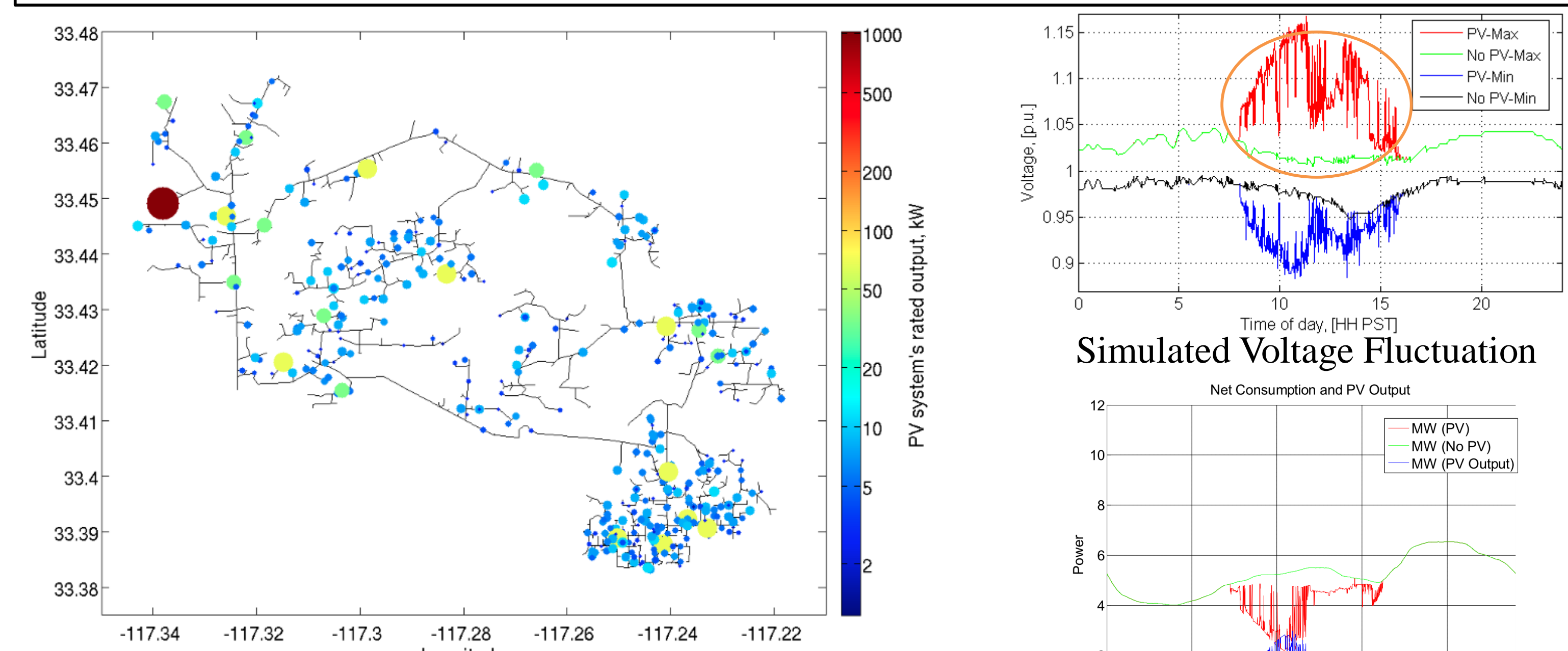


USI forecast's error metrics for all 31 days in Nov 2012. rMAE is 10% in average and increases as forecast horizon raises.

Issues with High PV Penetration

High PV penetration leads to various problems observed in both distribution and transmission systems:

- High frequency -> Impact frequency control and generators' synchronization -> power outage.
- Over-voltages -> damage electronic devices (light bulbs, computers, monitors, etc.)
- Voltage fluctuations -> shorten lifetime of voltage regulators, transformers, protection devices, etc.)

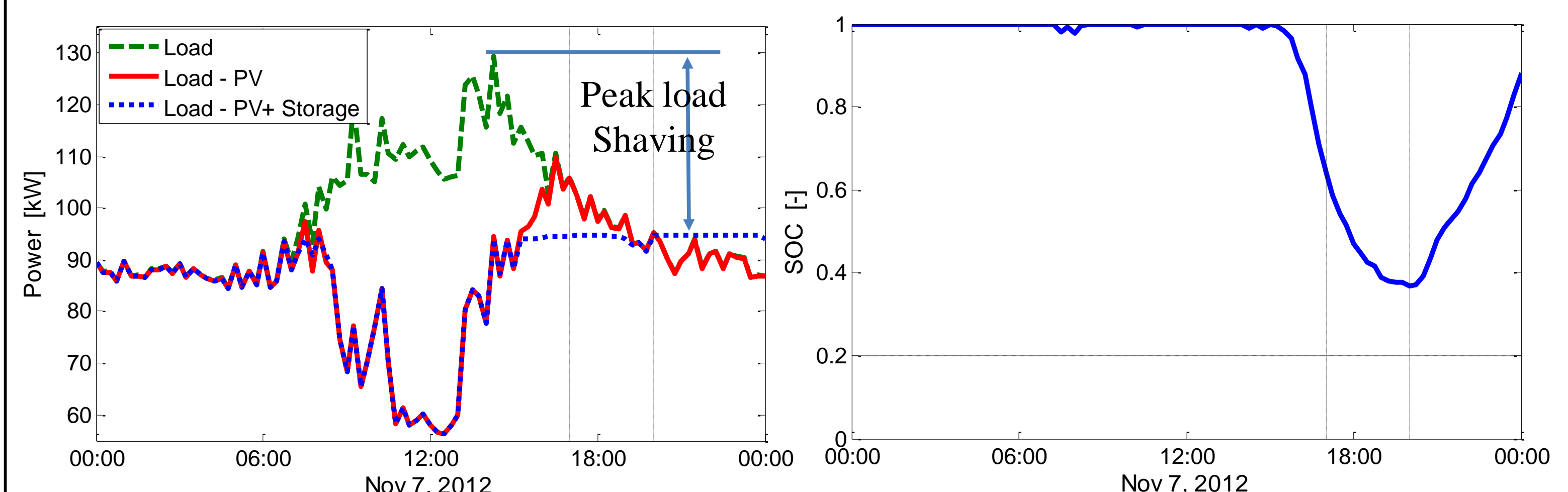


Real 12MW (1733 loads) SDGE distribution feeder with 2.3 MW PV. Simulated case with 5MW installed PV (42%) is shown.

Simulated Power Fluctuation

Peak load shaving control with Short-term Solar Forecast for Storage System

Control with Sky Imager Solar Forecast was developed for a 31kW PV tied to a 31 kWh Li-ion at John Hopkins parking structure at UCSD, CA. The solar forecasts was used to optimize the charge/discharge cycling for peak load shaving and battery life longevity. The strategy for peak load shaving is "Time-of-use Energy Cost Management Plus Demand Charge Management."



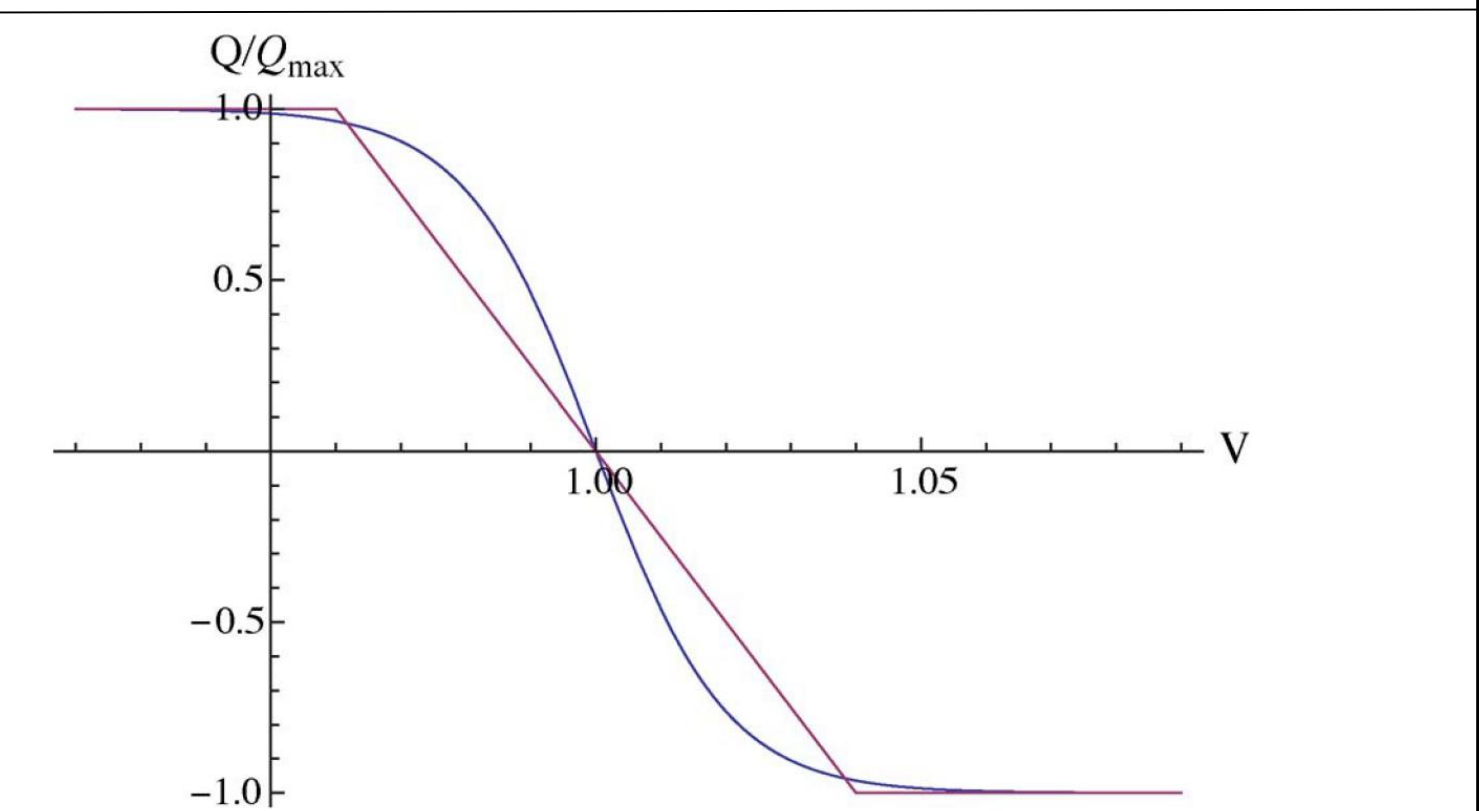
Control operation for Storage System at John Hopkins Building on Nov 7, 2012

	Optimization with PV Power Output and Load Forecast	Off-Peak/On-Peak without PV Power Output and Load Forecast
Annual energy bill cost reduction [\$]	33,200	30,500
Number of cycles at 80% DoD [cyc/yr]	212	365
Battery Lifetime [yrs]	14.2	8.2
Fixed cost simple payback time [yrs]	5.7	6.2
Total profit at end of battery lifetime (annual energy bill savings x battery lifetime - fixed costs) [\$]	281,000	60,000

Results in table below shows that the incorporation of forecast data was shown to dramatically increase system lifetime (6 years extra) and its lifetime profit (360% increase on a 31 kWh storage system).

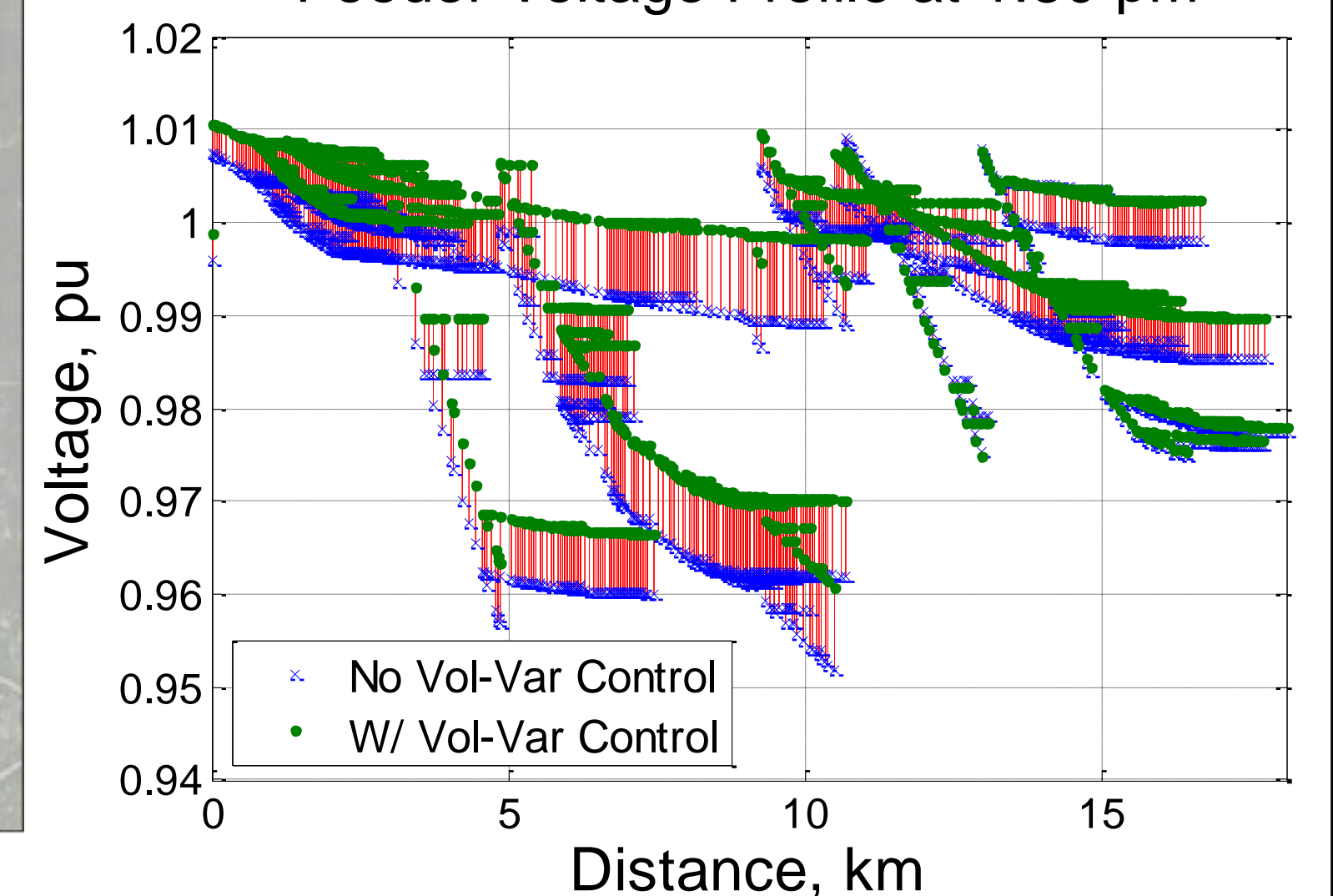
Local Vol-Var Control for PV Inverters

By combining USI-forecast and distribution system simulation using OpenDSS, we were able to design and demonstrate the impact of local volt-var control on the distribution network. With appropriate control design, the use of PV inverter reactive support will lessen the adverse impact of high PV penetration.

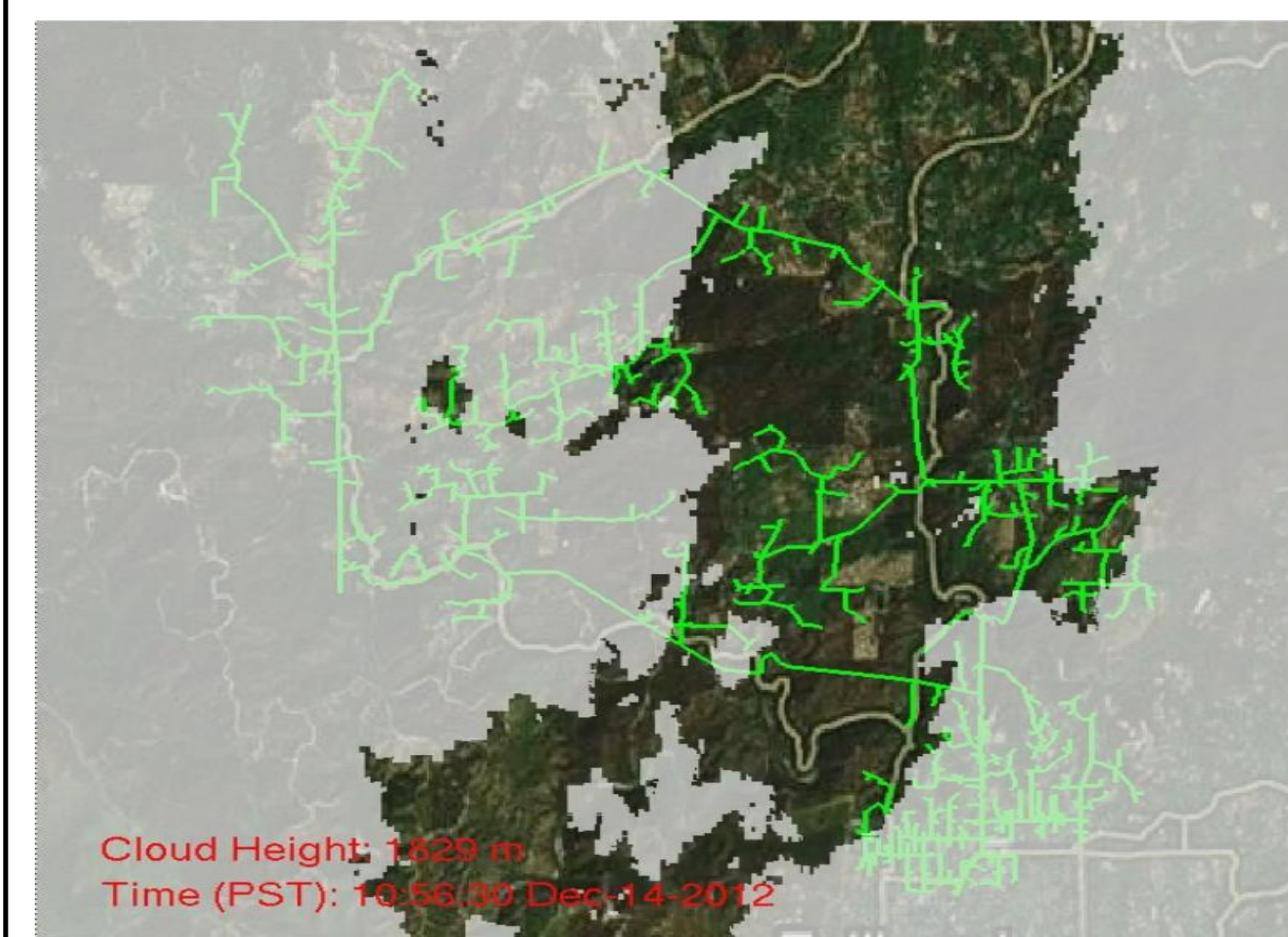


Local Vol-Var Control Scheme

Feeder Voltage Profile at 1:30 pm



Local Volt-Var control helps to bring the voltage level of the whole feeder up. The red lines show the increase in voltage levels along the feeder.



Cloud cover simulation on SDGE feeder using sky imager forecast. The green lines are feeder distribution lines. Whitish area is covered by cloud.

Centralized and Distributed Control for PV Inverters and ESSs

We are designing centralized and distributed control for multiple power inverters, storage systems, EV chargers, etc. for UCSD microgrid and SDGE feeders. The distributed control will (1) mitigate the impact of high penetration PV and (2) optimize the communication and interaction between all devices in smart grid setup.

$$\text{Cost: } J(u) = \sum_{t \in \tau} (J_{\text{loss}}(u(t)) + \delta J_{\text{power}}(u(t)))$$

Optimization Problem:

$$\begin{aligned} \min_{q_G, v} J \\ \text{s.t. } \forall t \in \tau \quad & \begin{cases} U_{\min} \leq \|u(t)\|_C \leq U_{\max}, & \forall l \in G, \\ V_{\text{dis}}^l \leq v_l(t) \leq V_{\text{ch}}^l, & \forall l \in G \cup S, \\ 0 \leq x_l(0) + \frac{1}{\beta_l} \sum_{s=1}^T v_l(s) \leq 1, & \forall l \in G \cup S, \\ \text{Power flow equations hold} \end{cases} \end{aligned}$$

